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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Patent Application of

PARSONS   Atty. Ref.: SCS-124-199

Serial No. 07/566,700   TC/A.U.: 3662

Filed: July 26, 1990   Examiner: D. Pihulic

For: REDUCTION OF LOW FREQUENCY VIBRATIONAL
     NOISE IN TOWED ARRAYS

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September 3, 2008

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

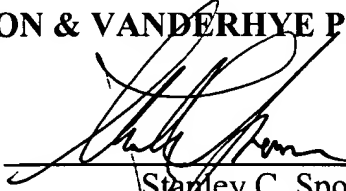### SUBMISSION OF PRIORITY DOCUMENTS

It is respectfully requested that this application be given the benefit of the foreign

filing date under the provisions of 35 U.S.C. §119 of the following, a certified copy of

which is submitted herewith:

Application No.	Country of Origin	Filed
8917275.3	GB	28 July 1989

Respectfully submitted,

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The Patent Office

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I, the undersigned, being an officer duly authorised in accordance with Section 62(3) of the Patents and Designs Act 1907, to sign and issue certificate on behalf of the Comptroller-General, hereby certify that annexed hereto is a true copy of documents as originally filed in connection with the patent application identified therein.

further certify that pursuant to Section 22(1) of the Patents Act, 1977, the Comptroller has rdered prohibition of publication of the said specification.

accordance with the Patents (Companies Re-registration) Rules 1982, if a company named this certificate and any accompanying documents, has re-registered under the Companies t 1980 with the same name as that with which it was registered immediately before re-istration save for the substitution as, or the inclusion as, the last part of the name of the rds "public limited company" or their equivalents in Welsh, references to the name of the pany in this certificate and any accompanying documents shall be treated as references e name with which it is so re-registered.

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istration under the Companies Act does not constitute a new legal entity but merely s he company to certain additional company law rules.

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An Executive Agency of the Department of Trade and Industry

PATENTS ACT 1977

PATENTS FORM NO. 1/77, (Revised 1982)

(Rules 16, 19)

The Comptroller
The Patent Office

REQUEST FOR GRANT OF A PATENT

8917275.3

THE GRANT OF A PATENT IS REQUESTED BY THE UNDERSIGNED ON THE BASIS OF THE PRESENT APPLICATION

I Applicant's or Agent's reference *(Please insert if available)*

D/PD PATS/P0729/AAS

II Title of invention
REDUCTION OF LOW FREQUENCY VIBRATIONAL NOISE IN TOWED ARRAYS

III Applicant or Applicants *(See note 2)*

Name (First or only applicant)........ The Secretary of State for Defence ....

Country. Great Britain. State................ADP Code No..............

Address . Whitehall, London, SW1A 2HB ....

....

Name (of second applicant, if more than one)................

.... Country .... State ....

Address ....

....

IV Inventor (see note 3)

(a) The applicant(s) is/are the sole/joint inventor(s)

or

(b) A statement on Patents Form No 7/77 is/will be furnished

V Name of Agent (if any) *(See note 4)*   R W Beckham

ADP CODE NO
1966001

VI Address for Service *(See note 5)* Procurement Executive, Ministry of Defence, Patents 1A(4), Room 2014, 20th Floor, Empress State Building, Lillie Road, London, SW6 1TR

VII Declaration of Priority *(See note 6)*

Country   Filing date   File number

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THE PATENT OFFICE
ROOM 331
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UNCLASSIFIED WHEN SEPARATED
FROM CLASSIFIED ENCLOSURES ....

VIII The Application claims an earlier date under Section 8(3), 12(6), 15(4), or 37(4) *(See note 7)*

Earlier application or patent number................and filing date..............

TSAF 0391

IX   Check List *(To be filled in by applicant or agent)*

A The application contains the following number of sheet(s)

1 Request . . . . One . . . . Sheet(s)

2 Description . . Eight . . . . Sheet(s)

3 Claim(s) . . . . Two . . . . Sheet(s)

4 Drawing(s) . . . One . . . . Sheet(s)

5 Abstract . . . . Sheet(s)

B The application as filed is accompanied by:-

1 Priority document . No

2 Translation of priority document   No

3 Request for Search . Yes . . . . . .

4 Statement of Inventorship and Right to Grant . . . . Yes . . . . . .

X   It is suggested that Figure No . . . . of the drawings (if any) should accompany the abstract when published

XI   Signature *(See note 8)*

NOTES:

1. This form, when completed, should be brought or sent to the Patent Office together with the prescribed fee and two copies of the description of the invention, and of any drawings.

2. Enter the name and address of each applicant. Names of individuals should be indicated in full and the surname or family name should be underlined. The names of all partners in a firm must be given in full. Bodies corporate should be designated by their corporate name and the country of incorporation and, where appropriate, the state of incorporation within that country should be entered where provided. Full corporate details, eg a "corporation organised and existing under the laws of the State of Delaware, United States of America", trading styles, eg "trading as xyz company", nationality, and former names, eg "formerly (known as) ABC Ltd" are *not* required and should *not* be given. Also enter applicant(s) ADP Code No. (if known).

3. Where the applicant or applicants is/are the sole inventor or the joint inventors, the declaration (a) to that effect at IV should be completed, and the alternative statement (b) deleted. If, however, this is not the case the declaration (a) should be struck out and a statement will then be required to be filed upon Patent Form No 7/77.

4. If the applicant has appointed an agent to act on his behalf, the agent's name and the address of his place of business should be indicated in the spaces available at V and VI. Also insert agent's ADP Code No. (if known) in the box provided.

5. An address for service in the United Kingdom to which all documents may be sent must be stated at VI. It is recommended that a telephone number be provided if an agent is not appointed.

6. The declaration of priority at VII should state the date of the previous filing and the country in which it was made and indicate the file number, if available.

7. When an application is made by virtue of section 8(3), 12(6), 15(4) the appropriate section should be identified at VIII and the number of the earlier application or any patent granted thereon identified.

8. Attention is directed to rules 90 and 106 of the Patent Rules 1982.

9. Attention of applicants is drawn to the desirability of avoiding publication of inventions relating to any article, material or device intended or adapted for use in war (Official Secrets Acts, 1911 and 1920). In addition after an application for a patent has been filed at the Patent Office the comptroller will consider whether publication or communication of the invention should be prohibited or restricted under section 22 of the Act and will inform the applicant if such prohibition is necessary.

10. Applicants resident in the United Kingdom are also reminded that, under the provisions of section 23 applications may not be filed abroad without written permission or unless an application has been filed not less than six weeks previously in the United Kingdom for a patent for the same invention and no direction prohibiting publication or communication has been given or any such direction has been received.

. . . SEPARATED
FROM CLASSIFIED ENCLOSURES

TSAF 0381

PATENTS ACT 1977

PATENTS FORM NO. 7/77 (Revised 1982)

(Rules 15, 82)

The Comptroller
The Patent Office

28 JUL 1989

PO729/AAS

8917275.3

STATEMENT OF INVENTORSHIP AND OF RIGHT TO THE GRANT OF A PATENT

I	Application No.

| II | Title | REDUCTION OF LOW FREQUENCY VIBRATIONAL NOISE IN TOWED ARRAYS |

III   I/We   The Secretary of State for Defence ....

....

....

the applicant(s) in respect of the above mentioned application for a patent declare as follows:-

i)   I/We believe the person(s) whose name(s) and address(es) are stated on the reverse side of this form (and supplementary sheet if necessary) is/are the inventor(s) of the invention in respect of which the above mentioned application is made;

ii)   The derivation of my/our right to be granted a patent upon the said application is as follows:

The inventor(s) is/are in employment under the Ministry of Defence and the invention belongs to the crown as represented by the Secretary of State for Defence by virtue of Section 39(1) of the Patents Act 1977.

iii)   I/We consent to the publication of the details contained herein to each of the inventors named on the reverse side of this form.

IV   *Signature*
    (see Note B)

    ....

    .....(R W Beckham) ..... REGISTERED PATENT AGENT ....

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T2DF 0222

PARSONS Alan

C/O Principle Directorate of Patents,
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Reduction of Low Frequency Vibrational Noise in Towed Arrays

The invention relates to linear arrays of sonar hydrophones adapted for towing behind ships and submarines and in particular to the reduction of the influence of vibrational noise on low frequency performance.

The acoustic part of a towed array of the type referred to herein comprises a number of sections, or modules, of long oil-filled hose containing hydrophones. Each module contains within the oil cavity, high modulus, longitudinal strength members, hereinafter referred to as internal strength members, whose main purpose is to support the tow load. In addition, there may exist longitudinal reinforcement embedded in the hose wall to prevent the latter from stretching. The two ends of each module are terminated in solid couplings which serve to join the sections together and to transfer the tow load from the hose wall to the internal strength members. It follows from this construction that if one of the couplings is vibrating longitudinally, whatever the source, then all the other couplings will be vibrating in some measure, since they are linked together by the high modulus internal strength members.

The primary sources of vibration are strumming of the tow cable, and snatching of the tow cable at the tow point when the towing vessel is in a heavy sea. Current methods for reducing the vibration are either to fair the cable or to insert vibration isolation modules between the cable and the array. These methods are not always totally efficient, and even when they are, there still exists a threshold level of vibration generated in the array itself by the action of the turbulent boundary layer.

It is known that the internal strength members are important transmitters of low frequency, longitudinal vibration. This sets the couplings into vibration which act as discrete sources of bulge waves (sometimes known as breathing waves) and longitudinal hose-wall elastic waves, each of which generate pressures inside the hose. Since these waves have long wavelengths at low frequencies they can propagate to the centre of a module with little attenuation from hose-wall damping. Reflections from adjacent couplings, partial reflections from internal components, and standing wave effects may

also be important.

It is evident that the resultant self-noise field due to low frequency vibration is not spatially homogeneous. In other words, the self-noise levels on single channels vary with position in the module. As a consequence, the familiar concept of wavenumber space that is so useful for interpreting the characteristics of the homogeneous pressure response at high frequencies, is no longer very useful at low frequencies. A related problem is that the spatial non-homogeneities render difficult any simple estimation of the array gain against self-noise to be applied to single channel levels.

The object of the present invention is to provide a means to improve the low frequency performance of towed sonar arrays when they are limited by the effects of vibration.

The invention provides a data processor for connection to a linear towed sonar array of the type hereinbefore defined, the processor being connectable to the hydrophones of the array such that at low frequencies the outputs from all the hydrophones in each respective module of the towed array are added together with uniform weighting and without relative phase delays so as to form respective single channel outputs.

The important feature of this summed output from each module is that at low frequencies it closely approximates the average internal pressure over the length of the module. The average pressure in the module due to low frequency vibration has been shown by theoretical analysis to approach zero. Thus by treating each module as a single channel the influence of low frequency vibration on the low frequency acoustic signals can be considerably reduced. Beamforming can then be done in a conventional manner with the weighted sum of a number of module outputs formed with phase delays appropriate to a selected beam direction.

Advantageously the Poisson ratio of the hose material is substantially equal to 0.5. This has been shown to reduce still further the effects of vibration on the low frequency performance of the towed array.

Preferably high modulus internal strength members are included in each array module to resist anti-phase vibration of the module end-couplings.

Advantageously the separation of the hydrophones in the array is small compared to the length of the array module, so that the summed outputs of the

discrete hydrophones closely approximate a continuous integral. In addition it is preferable that the coupling length is short compared to the module length.

In one arrangement an accelerometer may be provided in each module coupling to measure the respective vibrations at the ends of each module and to produce a signal therefrom to cancel the vibration noise in the hydrophone outputs. In another arrangement, provided the fill-fluid is substantially inviscid and provided the reflection coefficient of the bulkheads for bulge waves and elastic waves are substantially zero, it has been shown from theory that in general for an arbitrary configuration of hydrophones within the module, regardless of the hydrophone spacing, it is possible to choose a set of frequency dependent weights such that the sum of the weighted hydrophone outputs has zero response to low frequency vibration. Thus the invention can be modified by applying frequency-dependent weights when forming the array beams.

The invention will now be described by way of example only with reference to the accompanying Drawings of which:

Figures 1 and 2 illustrate one module of a towed sonar array in longitudinal and cross sections; and

Figure 3 shows a block diagram of a towed array signal processor arrangement to reduce the effect of vibration on the low frequency spectrum.

As shown in Figures 1 and 2 a towed sonar array comprises a number of similar acoustic modules 10 connected together by end couplings indicated by 11. Hydrophones 12 and their electronics cans 13 are supported on bulkheads 14 spaced along the module within an elastic hose 15 filled with a substantially incompressible fluid 16 to render the module neutrally buoyant. The bulkheads are themselves supported by the internal strength members 17. In one arrangement the hose may contain embedded longitudinal reinforcement 18 to prevent the hose stretching.

The internal strength members 17 readily transmit low frequency longitudinal vibrations which cause the end couplings 11 to vibrate. These vibrations generate bulge waves and longitudinal elastic waves in the hose wall 15, together with associated pressure fluctuations within the fluid 16 which are detected by the hydrophones 12 and constitute self-noise. The constructional features of the array exert a strong influence on the detailed

response of the array to vibration. Thus the resulting self-noise is complex and spatially inhomogeneous and is therefore dependent on the position of a hydrophone within the module 10.

Figure 3 shows a signal processing arrangement which has been devised to minimise the effect of vibration on a towed array operating at low frequencies. The array has n modules $10_1 \ldots 10_n$ each with m hydrophones. The outputs from the m hydrophones in each module are connected to respective adders $30_1 \ldots 30_n$ with no relative phase delays between the outputs from the hydrophones of any given module. Beamforming is then achieved by connecting the outputs from the adders $30_1 \ldots 30_n$ to respective phase delays $\triangle_1 \ldots \triangle_n$ which are set by a programmer 31 so as to form a beam in a predetermined direction as will be understood in the art. The phase delayed outputs from adders $30_1 \ldots 30_n$ are then summed by the adder 32 to provide a beam output 33.

The inventor has shown that an anti-symmetry exists in the pressure field inside an array module when the couplings 11 are vibrating in phase. The average pressure over the length of the module due to the vibration is then zero. This condition is assisted by employing high modulus internal strength members which connect together the couplings. In an alternative form the outputs of axial accelerometers located in the couplings could be used to cancel the vibrational component of the pressure response. The cancellation could be achieved deterministically if the hose parameters are known in advance, or it could be achieved adaptively.

The inventor has shown theoretically that the average pressure over the length of an array and the vibration levels at each end are connected by a simple relation. The relation is insensitive to the viscosity and compressibility of the fill-fluid and to the presence of internal strength members and bulkheads. The relation and its outline derivation are given below.

The following notation is employed:

x, r = longitudinal and radial coordinates

w = frequency

u = longitudinal displacement of hose wall

u_0 =   longitudinal displacement of vibrating coupling at x=0

u_L =   longitudinal displacement of vibrating coupling at x=L

w   =   radial displacement of hose wall

p   =   pressure in fill-fluid

E   =   longitudinal modulus of hose material

$\alpha^2 E$ =   circumferential modulus of hose material

δ =   Poisson ration of hose material

L   =   length of module

R   =   hose radius

ρ = density of fill-fliud

v   =   viscosity of fill-fluid

c_b =   bulge wave speed

c_p =   longitudinal elastic wave speed

c   =   sound speed in fill- fluid

The main assumptions are as follows:

1) The motion is circumferentially symmetric so that all dependent variables are functions only of the coordinates x and r.

2) The motion of the fill-fluid is governed by the linearised compressible Navier-Stokes equations and the linearised compressible continuity equation.

3) The motion of the hose wall is governed by the linearised cylindrical thin membrane equations. In particular, it is assumed that the longitudinal and circumferential stresses in the hose wall are related to the strains by

$$T_{xx} \;=\; \frac{E}{1 - \delta^2}\left(\frac{\partial u}{\partial x} + \alpha\delta\,\frac{w}{R}\right) \tag{1}$$

$$T_{\theta\theta} \;=\; \frac{E}{1 - \delta^2}\;\alpha\delta\frac{\partial u}{\partial x} + \alpha^2 \frac{w}{R} \tag{2}$$

The low frequency approximation holds, so that

$$R\omega/c_b \ll 1, \quad R\omega/c_p \ll 1, \quad R\omega/c \ll 1 \tag{3}$$

which are expected to be valid in typical arrays at low frequencies of interest. The approximations in Equation (3) imply that the effect of external fluid loading can be neglected and that the internal pressure is

essentially constant over the fluid cross-section.

The appropriate boundary conditions are continuity of normal and tangential displacement and continuity of normal and tangential stress at the hose wall, continuity of normal and tangential displacement at the couplings, and continuity of longitudinal hose wall displacement and average longitudinal fluid displacement across a bulkhead.

It can then be shown that the average pressure over the length of a module is:

$$\frac{1}{L}\int_0^L p.dx = \rho c_b^2 \left[\frac{(1 - 2\sigma/)-i w v(1-6^2)/c_b^2}{(1 - 6^2)(1 - i w v/3c^2) + c_b^2/c^2}\right] \frac{(u_L - u_0)}{L} \quad (4)$$

It may be verified that in typical situations the effect of viscosity in Equation (4) is small, so that it simplifies to:

$$\frac{1}{L}\int_0^L p.dx = - \frac{\rho c_b^2}{(1 - 6^2) + c_b^2/c^2}\left\{1 - \frac{26}{\alpha}\right\} \frac{(u_L - u_0)}{L} \quad (5)$$

This result exhibits no explicit frequency dependence and therefore applies even in the static case.

The result in Equation (5) forms the basis of the present invention. For example, it is evident that the average pressure over the length of the module vanishes if the couplings are vibrating in phase. It is also evident that the result can be readily extended to arrays comprising more than one module.

The significance of the factor $(1 - 26/\alpha)$ in Equation (5) will now be discussed.

If the hose is an isotropic medium because no reinforcing material is included then $\alpha = 1$ and for many hose materials of interest o is approximately equal to 0.5. Thus the factor $(1 - 26/\alpha)$ is close to zero and the average internal fluid pressure p due to the vibrational displacements is also a small quantity. If, however, the hose is anisotropic by virtue of longitudinal reinforcement the hose is much stiffer longitudinally than circumferentially. Hence we would not expect a given circumferential strain to produce much Poisson-coupled longitudinal strain, since this would be resisted by the large longitudinal modulus. Thus by reference to Equation

(1) we would expect the product $\alpha\delta$ to be small. Conversely, we would expect a given longitudinal strain to produce a Poisson-coupled circumferential strain very similar to that in the isotropic case, because the circumferential modulus should be little affected by the presence of longitudinal reinforcement. By reference to Equation (2) this implies that the ratio δ/α should remain roughly equal to the Poisson ratio of the matrix material within which the reinforcement is embedded.

It has been further shown that the above arguments can be supported by theoretical analysis. In particular it can be shown that since the Poisson ratios of the component materials cannot be greater than 0.5, the ratio δ/α also cannot be greater than 0.5. Thus the factor $(1 - 2\delta/\alpha)$ must be positive, as in the isotropic case. Furthermore, if the Poisson ratios of the component materials are each close to 0.5 then $(1 - 2\delta/\alpha)$ is a small quantity, as in the isotropic case and the average pressure in Equation (5) is also small.

The inventor has also shown that if in the process of beamforming relative phase delays are introduced between hydrophones in any given module, as is done conventionally, then the beamformed response of the array to low frequency vibrational noise is generally greater than that obtained when no such phase delays are included.

Thus it has been shown that:
a) The average internal pressure in the fluid of a towed array is generated by the tendency of the strained hose to produce an internal volume change; a pure translation of the hose produces no strain, no internal volume change, and hence no average internal pressure, even though the pressures at individual points along the array may be non-zero.
b) If the Poisson ratios of the materials of the hose are equal to 0.5 then the average internal pressure response vanishes. This should apply even if the hose contains longitudinal reinforcement.
c) Problems associated with the spatial non-homogeneity of the pressure patterns produced by the elastic waves and bulge waves generated by the vibration are avoided by considering the average pressure over the length of a module.
d) By virtue of (a) and (b) above the response of the array to the effects of

low frequency vibration are reduced by summing the hydrophones within a module without phase delays.

The results thus far relate to average pressure in a section terminated at each end by solid diaphragms. In a towed array these diaphragms are the couplings between adjacent modules. The results can be applied equally to a number of modules with the difference in vibrational levels between the ends being related to the average pressure in the modules. Thus the sonar array could conceivably be arranged with modules in groups of 2 or more with constant phase differences applied to the groups.

Claims

1. A data processor for connection to a linear towed sonar array of the type hereinbefore defined, the processor being connectable to the hydrophones of the array such that at low frequencies the outputs from all the hydrophones in each respective module of the towed array are added together with uniform weighting and without relative phase delays so as to form respective single channel outputs.

2. A data processor as claimed in claim 1 wherein beamforming is done by providing phase delays in the processor such that the weighted sum of a number of module outputs can be formed by means of phase delays appropriate to a selected beam direction.

3. A data processor as claimed in claim 2 wherein a set of frequency dependent weights is selected for beamforming on connection to the module outputs such that the sum of the weighted hydrophone outputs has zero response to low frequency vibration.

4. A sonar detection system including a data processor as claimed in any one of claims 1 to 3 wherein the hose material is selected such that the Poisson ratio is substantially equal to 0.5.

5. A sonar detection system including a data processor as claimed in any one preceding claim wherein high modulus internal strength members are included in each array module to resist anti-phase vibration of the module end-couplings.

6. A sonar detection system including a data processor as claimed in any one preceding claim wherein the separation of the hydrophones in the array is small compared to the length of the array module, so that the summed outputs of the discrete hydrophones closely approximate a continuous integral.

7. A sonar detection system including a data processor as claimed in any one preceding claim wherein the module coupling length is short compared to the module length.

8. A sonar detection system including a data processor as claimed in any one preceding claim wherein an accelerometer is provided in each module coupling to measure the respective vibrations at the ends of each module and to produce a signal therefrom connectable to the data processor to cancel the vibration
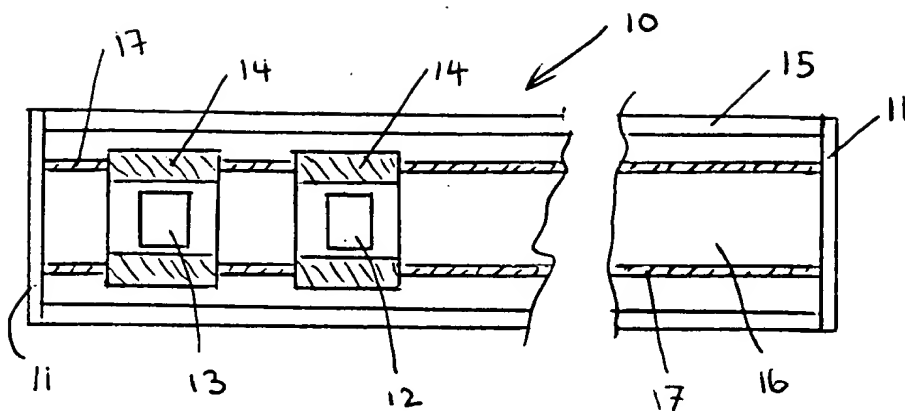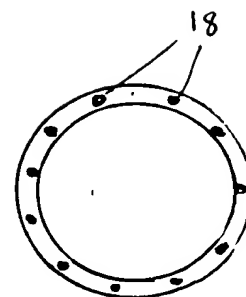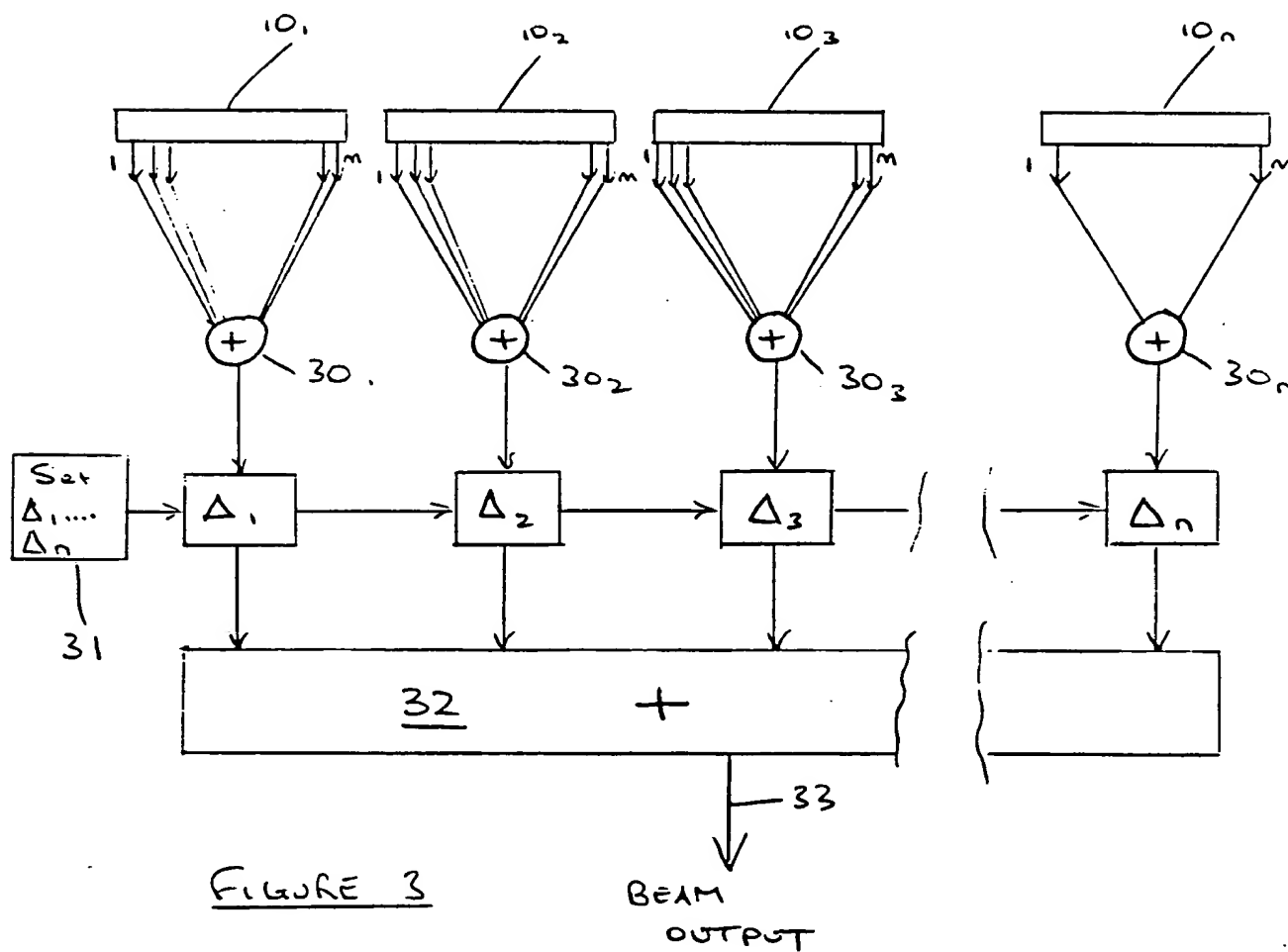
noise in the hydrophone outputs.

FIGURE 1

FIGURE 2

FIGURE 3

BEAM
OUTPUT